In-Season Optimization and Site-Specific Nitrogen Management for Soft Red Winter Wheat

Michael Flowers,* Randall Weisz, Ronnie Heiniger, Deanna Osmond, and Carl Crozier

ABSTRACT

Site-specific N management based on an in-season assessment of crop N status may offer producers increased grain yield, profitability, and spring N fertilizer use efficiency (SNUE). The goal of this study was to determine the distinct contributions of (i) in-season N rate optimization and (ii) site-specific N management. Our objective was to compare site-specific and field-specific N management with typical growers' practices to determine if site-specific N management (i) increased soft red winter wheat (*Triticum aestivum* L.) grain yield, (ii) reduced N inputs, (iii) increased SNUE, and (iv) reduced within-field grain yield variability. Research was conducted at eight sites in 2000, 2001, and 2002. A randomized complete block design with two or five N management systems was used at two and six sites, respectively. Site-specific management did not improve grain yield compared with field-specific management when based on the same in-season estimation of optimum N rates. At sites where site-specific or field-specific systems were compared with typical growers' practices, grain yield benefits of in-season N optimization (up to 2267 kg ha^{-1}) were apparent. For grain yield, in-season optimization of N rate was more important than site-specific management. A large reduction in N inputs (up to 48.6%) was also attributed to in-season N rate optimization. After incorporating in-season optimization, a further reduction in N inputs (up to 19.6%) was possible through site-specific application. Site-specific N application maximized SNUE compared with either field-specific or typical growers' practices at all sites and reduced within-field grain yield variance at four sites.

Site-specific N management is the adjusting of within-field N fertilizer rates based on spatially variable factors that affect optimum N rate (Sawyer, 1994). This practice may offer producers the ability to increase grain yield, profitability, and N fertilizer efficiency by applying N only where required for optimum plant growth. Site-specific management may also be environmentally beneficial to producers.

Mulla et al. (1992) created site-specific management units (18.3 m by 564–655 m) based on preseason soil N (nitrate N and ammonium N) tests and available soil water content. Similarly, Bhatti et al. (1998) created site-specific N management units based on crop productivity. In both cases, site-specific N reduced N fertilizer application up to 70% without a reduction in grain yield compared to a grower's practice.

Stone et al. (1996) used an on-the-go sensor measuring plant N spectral index to create submeter site-specific N management units based on an estimate of in-season crop N status in wheat. This site-specific N management system reduced N fertilizer by 32 and 57 kg N ha^{-1} at two of three sites without a reduction in grain yield compared with a typical grower's practice. They also reported that the site-specific N application reduced spatial variation in wheat forage and grain yield compared with the grower's practice.

Similarly, Raun et al. (2002) used a multispectral optical sensor to create 1-m^2 site-specific N management units in wheat. A N fertilizer optimization algorithm (NFOA) that estimates in-season crop N status and potential grain yield was used to adjust N rates. They reported that by using NFOA, it might be possible to set more efficient and profitable fertilization levels and increase N use efficiency compared with typical growers' practices.

Mulla et al. (1992), Bhatti et al. (1998), Stone et al. (1996), and Raun et al. (2002) compared site-specific N management based on either a pre- or in-season estimate of the crop's N requirement to a typical grower's practice. Consequently, the reduction in N rates compared with growers' practices might not have been the result of site-specific application but could instead be due to using a pre- or in-season estimation of the crop's N requirement.

In the southeastern USA, Scharf and Alley (1993), Alley et al. (1994), Weisz and Heiniger (2000), and Weisz et al. (2001) developed a field-specific N management system for soft red winter wheat based on an in-season evaluation of the crop's N requirement (Fig. 1). This system first determines the whole-field tiller density at Zadoks' Growth Stage (GS) 25 (Zadoks et al., 1974). When GS-25 tiller density is below a critical threshold (540 tillers m^{-2}), a GS-25 N application is made to increase tiller development (Ayoub, 1974; Power and Alessi, 1978; Lutcher and Mahler, 1988; Scharf and Alley, 1993; Weisz et al., 2001). A GS-25 N application can stimulate tiller development in southeastern areas because winter wheat does not enter a dormant state in these southern latitudes. If GS-25 tiller density is above the threshold, a GS-25 N application is not necessary. At GS 30, a field-averaged tissue test is used to optimize N application rates (Alley et al., 1994). This system resulted in an increase in estimated profit of \$73 ha^{-1} across 20 site-years (Scharf and Alley, 1993).

While this system (Fig. 1) has been tested and adopted

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Abbreviations: GS, growth stage; SNUE, spring nitrogen fertilizer use efficiency.

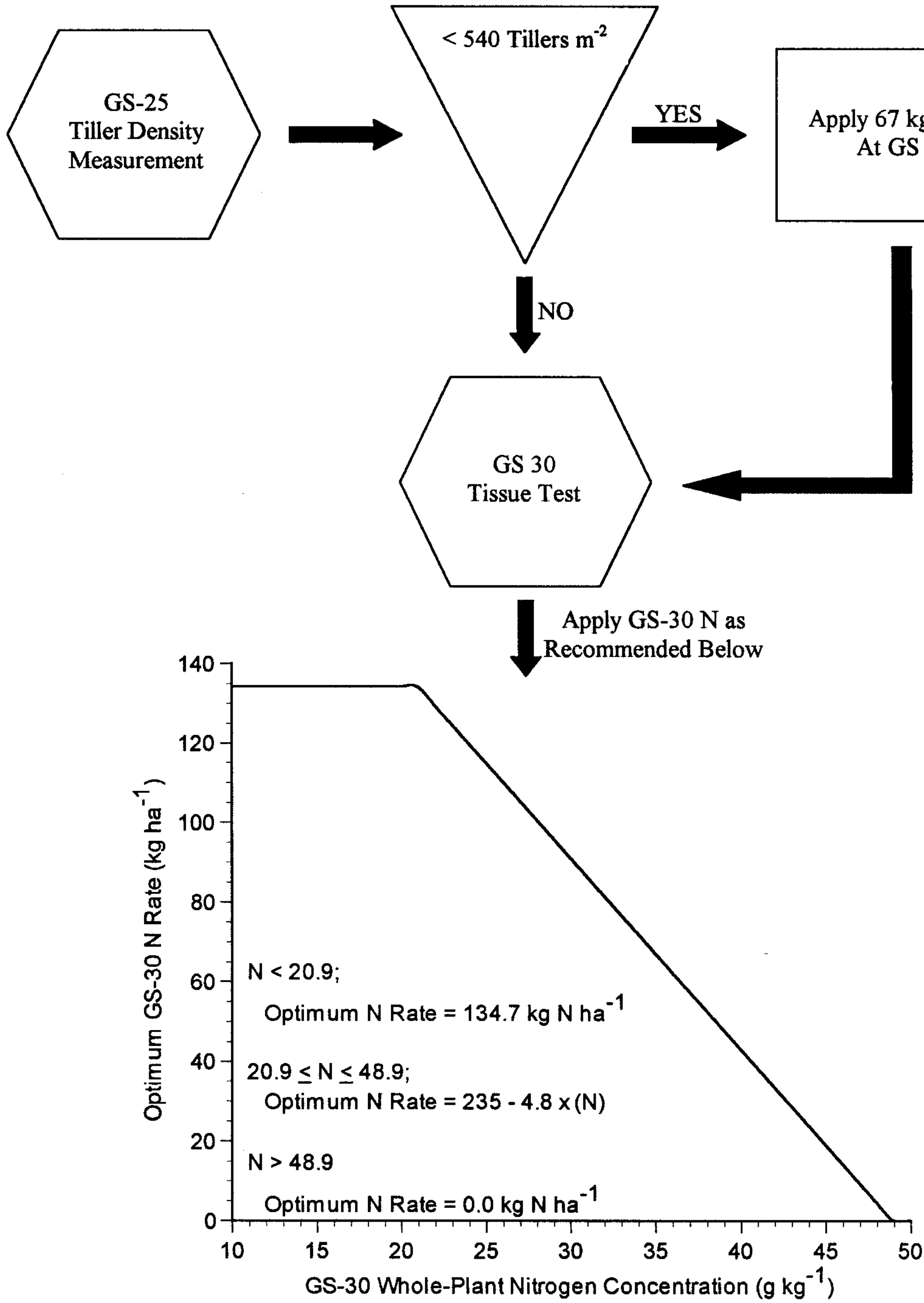

Fig. 1. Flow chart depicting the N recommendation system for soft red winter wheat (Weisz and Heiniger, 2000). Hexagons represent field measurements, triangles represent decisions, and rectangles represent N applications. Optimum growth stage (GS)-30 N rate vs. whole-plant N concentration at GS 30 from Alley et al. (1994) and Scharf and Alley (1993).

for whole-field use, it also has the potential to be used on a site-specific basis. This could be especially important for increasing N fertilizer efficiency in the humid southeast where sandy soils and high rainfall amounts in the fall and winter cause leaching or denitrification of N fertilizer applied before winter wheat planting (Scharf et al., 1993; Scharf and Alley, 1993).

Substantial reductions in N inputs have been reported for both site-specific and field-specific N management systems that are based on an in-season assessment of the crop's N requirements compared with growers' practices. The site-specific experiments of Mulla et al. (1992), Bhatti et al. (1998), Stone et al. (1996), and Raun et al. (2002) have these two factors confounded, and the importance of site-specific N management alone is left uncertain. In this light, our goal was to determine the distinct contributions of (i) in-season N rate optimization and (ii) site-specific N management on the large reductions in N inputs previously reported. Our objective was to compare site-specific and field-specific N management (based on Fig. 1) with typical growers' practices to determine if site-specific N management (i) increased grain yield, (ii) reduced N inputs, (iii) increased SNUE, and (iv) reduce within-field grain yield variability.

MATERIALS AND METHODS

Site Description

Research was conducted in the North Carolina coastal plain and piedmont at eight sites in 2000, 2001, and 2002. In 2000, two on-farm sites (W1 and W2) in Wilson, NC, were used. In 2001 and 2002, studies were located at the Piedmont Research Station (P1 and P2) in Salisbury, NC, and at four sites located in Kinston, NC, at the Cunningham Research Station (K1) and the Lower Coastal Plain Tobacco Research Station (K2, K3, and K4). Field sizes ranged from 14.3 ha at W2 to 0.75 ha at K1. Table 1 describes the soils, wheat cultivars, tillage, and N management systems at each site.

Starter N applications (22.5 kg ha^{-1}) were applied at K1, K2, K3, and K4 based on North Carolina standard recommendations (Weisz and Heiniger, 2000) for early planted wheat. Sites W1 and W2 did not receive starter N based on North Carolina standard recommendations (Weisz and Heiniger, 2000) for late-planted wheat. At P1 and P2, a starter N application was not applied due to expected carryover of N from the previous corn (*Zea mays* L.) crop. Phosphorus, K, and lime were applied at each site according to standard North Carolina recommendations (Tucker et al., 1997) based on preseason soil test results.

Nitrogen Management Systems

Five N management systems were tested and are described below.

The control did not receive any spring N. This management system was used as a baseline to determine SNUE.

Southeastern winter wheat growers typically apply N anytime between GS 25 and GS 30. To capture this range in practices, a GS-25 N application of 134.7 kg ha^{-1} (GP1) and a GS-30 N application of 134.7 kg ha^{-1} (GP2) were included.

The field-specific (FSN) system was based on Fig. 1. If the average GS-25 tiller density for the FSN plots was below threshold, a GS-25 N application of 67 kg ha^{-1} was applied. If the average GS-25 tiller density was above threshold, N was not applied at GS 25. Likewise, the average whole-plant N concentration at GS 30 was used to determine the FSN N rate at GS 30 (Fig. 1).

The site-specific (SSN) system was also based on Fig. 1; however, these GS-25 and GS-30 N rates were determined for individual subplot management units (see Experimental Design below).

Experimental Design

At W1 and W2, a randomized complete block design with four replications was used. Treatments consisted of SSN and FSN (Table 1). The SSN plots were split into 12 (W2) or 16 (W1) management units (i.e., each management unit received a N rate based solely on its properties), which were 15.4 by 15.4 m in size so that a commercial broadcast applicator could be used to apply N (34–0–0).

At P1, P2, K1, K2, K3, and K4, a randomized complete block design with six replications was used. Treatments consisted of SSN, FSN, GP1, GP2, and the control (Table 1). All SSN plots were divided into 4.6- by 9.1-m management units, resulting in four (P1), five (K1, K3, K4, and P2), or six (K2) management units per SSN plot. These smaller management units had N (30–0–0) applied using a custom-built research applicator.

Table 1. Site, soil type, soil taxonomic name, wheat cultivar, tillage, and N management system [SSN: site-specific N management; FSN: field-specific N management; GP1: a typical grower's practice applied at growth stage (GS) 25; GP2: a typical grower's practice applied at GS 30; Control: did not receive any spring N] at each of the eight sites.

Site	Soil type	Taxonomic name	Wheat cultivar	Tillage	N management system
W1	Appling–Marlboro complex	clayey, kaolinitic, thermic Typic Kanhapudults	FFR 555	conventional	SSN FSN
W2	Faceville sandy loam	clayey, kaolinitic, thermic Typic Kandiudults	FFR 518	no-till	SSN FSN
K1	Lynchburg sandy loam	fine, loamy, siliceous, thermic Aeric Paleaquults	Coker 9704	conventional	SSN FSN GP1 GP2 Control
K2	Goldsboro loamy sand	fine, loamy, siliceous, thermic Aquic Paludults	Pioneer 26R91	conventional	SSN FSN GP1 GP2 Control
K3	Norfolk loamy sand	fine, loamy, siliceous, thermic Typic Paleudults	Pioneer 2580	conventional	SSN FSN GP1 GP2 Control
K4	Goldsboro loamy sand	fine, loamy, siliceous, thermic Aquic Paludults	Roane	conventional	SSN FSN GP1 GP2 Control
P1	Hiwassee clay loam	fine, kaolintic, thermic Typic Rhoudults	Coker 9704	no-till	SSN FSN GP1 GP2 Control
P2	Hiwassee clay loam	fine, kaolintic, thermic Typic Rhoudults	Coker 9704	no-till	SSN FSN GP1 GP2 Control

Data Collection

Growth Stage-25 Tiller Density

In the K1, K2, K3, K4, P1, and P2 FSN management system, GS-25 tiller density was sampled at the plot centers. At each sampling location, tillers in two 1-m sections of row were counted. The FSN GS-25 tiller density was then determined by averaging the values found at all FSN sample locations. In the SSN management system, GS-25 tiller density was sampled in two 1-m sections of row at the center of each SSN management unit and the average of these two samples assigned to that SSN management unit. After GS-25 tiller density was determined, FSN and SSN GS-25 N rates were determined using Fig. 1.

Whole-Plant Nitrogen Concentration at Growth Stage 30

In the K1, K2, K3, K4, P1, and P2 FSN, GP1, GP2, and control management systems, GS-30 whole-plant N concentration was sampled at two locations within each plot. At W1 and W2, FSN whole-plant N concentration at GS 30 was sampled at a single location at the plot centers. At each sampling location, all plant tissue above the soil surface in two 1-m sections of row was collected, dried, and analyzed for whole-plant N concentration using a CHN analyzer (McGeehan and Naylor, 1988). The FSN, GP1, GP2, and control whole-plant N concentration at GS 30 was then determined by averaging the values found at all FSN, GP1, GP2, and control sample locations. In the SSN management system, whole-plant N concentration at GS 30 was sampled in two 1-m sections of row at the center of each SSN management unit and the average of these two samples assigned to that SSN management unit. After whole-plant N concentration at GS 30 was determined, FSN and SSN GS-30 N rates were determined using Fig. 1.

Grain Yield and Nitrogen Concentration

Grain yield was determined at each site using a Massey Ferguson MF-8 combine (AGCO Corp., Duluth, GA) with a grain gauge and moisture sensor (Juniper Syst., Logan, UT). Grain yields were adjusted to 135 g kg^{-1} moisture for analysis. At W1 and W2, grain yield was determined for each plot by harvesting and averaging three 2.1- by 61-m within-plot strips. At the remaining six sites, grain yield was determined by harvesting the center 2.1-m-wide strip from each plot. A 2.3-kg grain sample was collected from each plot at all locations for grain N concentration analysis using a CHN analyzer (McGeehan and Naylor, 1988).

Straw Yield and Nitrogen Concentration

At W1 and W2, wheat straw was removed and separated from the grain by the combine in a subsection (approximately 10 m long) of each within-plot strip and weighed in the field. A 100-g straw subsample was also weighed in the field, dried, and then reweighed to determine straw moisture content. Average straw dry weight was then determined for each plot. At the remaining six sites, straw fresh weight was determined for all straw separated from the grain within a plot. Subsamples were collected and dried, and plot dry weight was determined as described above. For all plots and sites, a straw sample was analyzed for N concentration using a CHN analyzer (McGeehan and Naylor, 1988).

Data Analysis

Histograms of SSN whole-plant N concentration at GS 30 for each site were produced from the data collected in each management unit. Histograms provided a means of examining the range of within-field variability in whole-plant N concentration and were used to estimate the percentage of land area to which FSN may have over- or underapplied N.

The SNUE for SSN, FSN, GP1, and GP2 were calculated as:

$$\mathrm{SNUE_{TRT}} = [(\mathrm{GY_{TRT}} \times \mathrm{GN_{TRT}} + \mathrm{SY_{TRT}} \times \mathrm{SN_{TRT}}) - (\mathrm{GY_{Control}} \times \mathrm{GN_{Control}} + \mathrm{SY_{Control}} \times \mathrm{SN_{Control}})]/\mathrm{SpringN_{TRT}} \quad [1]$$

where $\mathrm{SNUE_{TRT}}$, $\mathrm{GY_{TRT}}$, $\mathrm{GN_{TRT}}$, $\mathrm{SY_{TRT}}$, $\mathrm{SN_{TRT}}$, $\mathrm{SpringN_{TRT}}$ are the SNUE, grain yield, grain N concentration, straw yield, straw N concentration, and spring N applied, respectively, for the N management system of interest. Grain yield, grain N concentration, straw yield, and straw N concentration for the control system are represented as $\mathrm{GY_{Control}}$, $\mathrm{GN_{Control}}$, $\mathrm{SY_{Control}}$, and $\mathrm{SN_{Control}}$, respectively. This definition of SNUE estimates the fraction of spring-applied N sequestered by the crop and which was, therefore, not lost (through leaching or denitrification) to the environment. This contrasts with other estimations of N use efficiency that only account for grain N and ignore N that is sequestered in straw (Raun and Johnson, 1999).

At K1, K2, K3, K4, P1, and P2, an estimate of between-plot (within-field) variance for each management system was calculated. General Linear Models analysis (SAS Inst., 1998) was used to calculate mean squares for subplot grain yields by management system. Management systems with the lowest mean squares were assumed to have minimized between-plot (within-field) variance.

At all sites, N management effects on whole-plant N concentration at GS 30, grain yield, and SNUE were tested with ANOVA (General Linear Models, SAS Inst., 1998). Means were separated using least square means.

RESULTS AND DISCUSSION

W1

Mean GS-25 tiller density was below the critical threshold (540 tillers m^{-2}) for FSN and all SSN management units (Table 2), but excessive rain did not permit the recommended GS-25 N to be applied. Consequently, until GS 30, both SSN and FSN were managed identically, and their mean whole-plant N concentrations were not statistically different (Table 2). The histogram of SSN whole-plant N concentration (Fig. 2) shows that values ranged from 22.5 to 43.6 g kg^{-1}, corresponding to recommended GS-30 N rates from 25.7 to 127.0 kg N ha^{-1}. The histogram also indicates that a uniform N application based on the FSN mean overapplied N to 75.0% of the field. The SSN system applied 19.6% less spring N than FSN (Table 2) without a significant reduction in grain yield (Fig. 3). This reduction in N input may be due to a skewed frequency distribution of whole-plant N concentration at GS 30. If the mean whole-plant N concentration at GS 30 is lower than the median (a frequency distribution that is skewed to the left), an overapplication of N will result (Hergert et al., 1997). The W1 histogram (Fig. 2) is based on too small a sample size for statistics of skewness to be reliable, but it appears to be skewed to the left, which may explain why SSN resulted in a reduced N rate compared with FSN.

Table 2. Site, N management system [SSN: site-specific N management; FSN: field-specific N management; GP1: a typical grower's practice applied at (GS)25; GP2: a typical grower's practice applied at GS 30; Control: did not recieve any spring N], mean GS-25 tiller density, percentage of plots receiving GS-25 N, mean GS-30 whole-plant N concentration, mean GS-30 N application rate, and mean total spring N rate for each of the eight sites.

Site	N management system	Mean GS-25 tiller density	Percentage of plots receiving GS-25 N		Mean GS-30 whole-plant N concentration	Mean GS-30 N application rate	Mean total spring N rate
			67 kg ha^{-1}	134 kg ha^{-1}			
		tillers m^{-2}	%		g kg^{-1}	kg ha^{-1}	
W1	SSN	302	0†	0	33.6‡	72.8	72.8
	FSN	267	0†	0	30.1a	90.5	90.5
W2	SSN	345	100	0	41.9a	35.9	101.5
	FSN	372	100	0	37.6a	54.5	121.5
K1	SSN	535	28	0	28.3b	96.8	124.0
	FSN	544	0	0	27.0b	114.5	114.5
	GP1	–	0	100	41.7a	0	134.7
	GP2	–	0	0	27.1b	134.7	134.7
	Control	–	0	0	24.9b	0	0
K2	SSN	349	100	0	45.1ab	16.1	86.7
	FSN	340	100	0	43.1b	33.7	99.9
	GP1	–	0	100	48.3a	0	134.7
	GP2	–	0	0	32.9c	134.7	134.7
	Control	–	0	0	31.5c	0	0
K3	SSN	705	0	0	19.9b	134.3	134.3
	FSN	678	0	0	19.6b	134.7	134.7
	GP1	–	0	100	34.8a	0	134.7
	GP2	–	0	0	19.7b	134.7	134.7
	Control	–	0	0	20.0b	0	0
K4	SSN	648	3	0	17.9b	132.5	134.7
	FSN	609	0	0	17.5b	134.7	134.7
	GP1	–	0	100	33.0a	0	134.7
	GP2	–	0	0	17.5b	134.7	134.7
	Control	–	0	0	17.8b	0	0
P1	SSN	288	100	0	52.2b	5.9	73.2
	FSN	293	100	0	51.5b	0	69.3
	GP1	–	0	100	60.0a	0	134.7
	GP2	–	0	0	38.6c	134.7	134.7
	Control	–	0	0	39.6c	0	0
P2	SSN	767	0	0	22.0b	127.6	127.6
	FSN	798	0	0	21.5b	131.8	131.8
	GP1	–	0	100	33.4a	0	134.7
	GP2	–	0	0	24.9b	134.7	134.7
	Control	–	0	0	22.8b	0	0

† Management system recommended a GS-25 N application that was not applied due to poor weather conditions.
‡ Means followed by the same letter are not significantly different at the 0.05 level.

W2

The mean FSN and all SSN management units had a GS-25 tiller density below the critical threshold (Table 2), and 67 kg N ha^{-1} was applied to both systems at GS 25. As at W1, until GS 30, both of these systems were managed identically, and there was not a statistical difference between them in mean whole-plant N concentration at GS-30. The SSN histogram (Fig. 2) shows that whole-plant N concentration at GS 30 ranged from 24.4 to 61.4 g kg^{-1}, corresponding to recommended N rates from 0.0 to 117.9 kg N ha^{-1}. It also indicates that FSN overapplied N to 82.6% of the field. The SSN systems applied 16.5% less spring N (Table 2) without a significant reduction in grain yield (Fig. 3) compared with FSN.

K1

At GS 25, 28% of the SSN management units had tiller densities below the threshold and received 67 kg N ha^{-1} (Table 2). Mean FSN tiller density was above the threshold, and thus, N was not applied at GS 25. The GP1 system received 134.7 kg N ha^{-1} as defined.

At GS 30, values of mean whole-plant N concentration for each system (Table 2) were consistent with the amount of N applied earlier at GS 25. The FSN, GP2, and control did not have N applied at GS 25 and had the lowest values of whole-plant N concentration at GS 30 (27.0, 27.1, and 24.9 g kg^{-1}, respectively). The SSN system in which 28% of the management units received 67 kg N ha^{-1} at GS 25 had a slightly higher (but not statistically different) whole-plant N concentration at GS 30 (28.3 g kg^{-1}). The highest mean whole-plant N concentration was in GP1 (41.7 g kg^{-1}) and was consistent with a high GS-25 N rate.

The histogram of SSN whole-plant N concentration at GS 30 (Fig. 2) ranged from 23.2 to 49.6 g kg^{-1} corresponding to recommended N rates from 0.0 to 123.6 kg N ha^{-1}. Because 28% of the SSN management units received GS-25 N, this histogram could not be used to estimate the frequency distribution of FSN whole-plant N concentration at GS 30 or the fraction of the field to which FSN may have over- or underapplied N (i.e., the distribution of SSN whole-plant N concentration at GS 30 was not the same as the FSN distribution). While SSN applied less GS-30 N, when combined with what was applied at GS 25, SSN applied 8.3% more total spring N than the FSN system (Table 2). Compared with GP1 and GP2, both of which applied a total spring

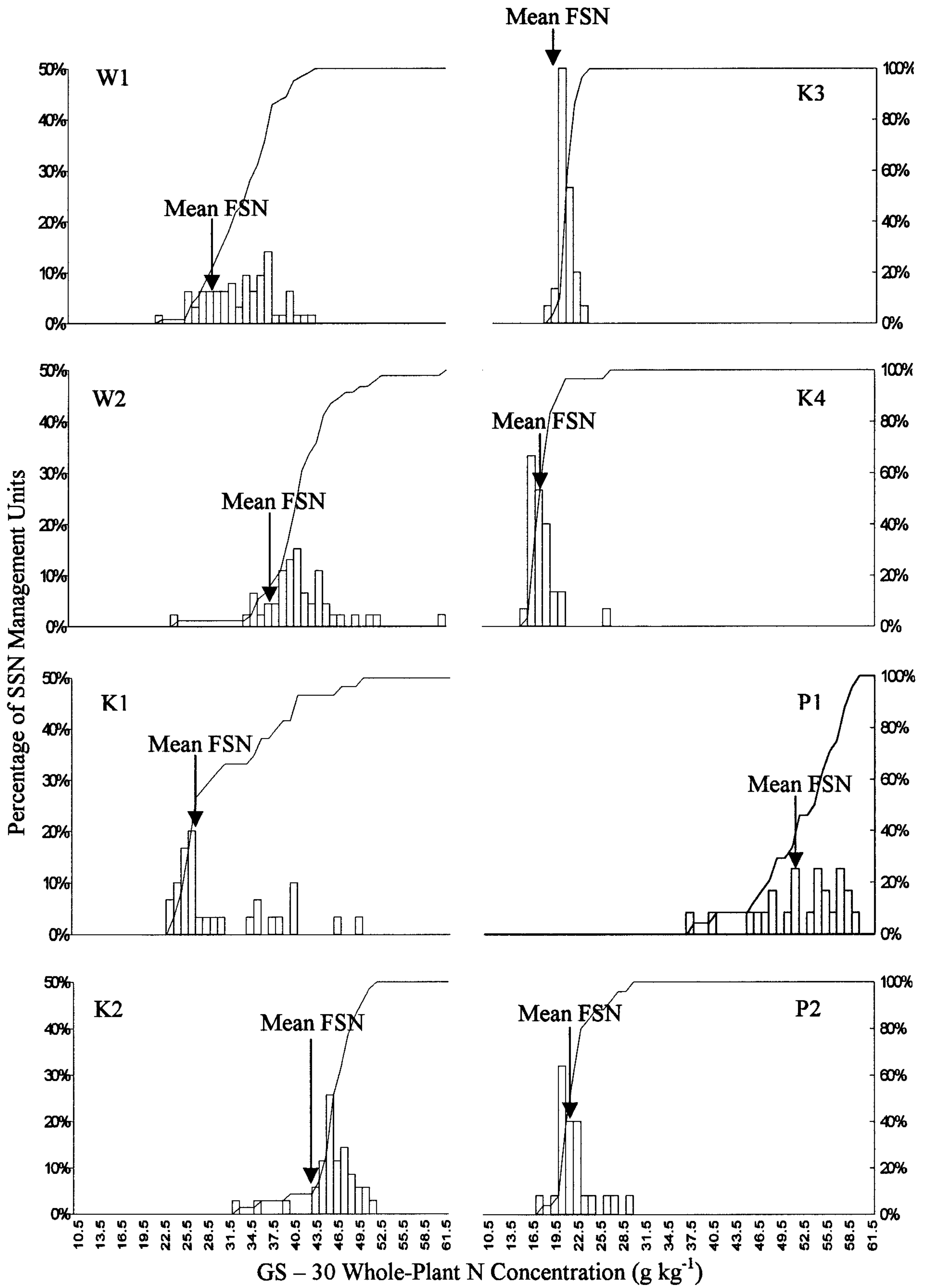

Fig. 2. Histograms of whole-plant N concentrations at growth stage (GS) 30 for the SSN management units at each of the eight sites. The primary axis and bars describe the percentage of SSN management units at a given GS-30 whole-plant N concentration. The secondary axis and line graph describe the cumulative percentage of SSN management units at or below a given GS-30 whole-plant N concentration. The mean FSN whole-plant N concentration at GS 30 at each site is also indicated on each histogram.

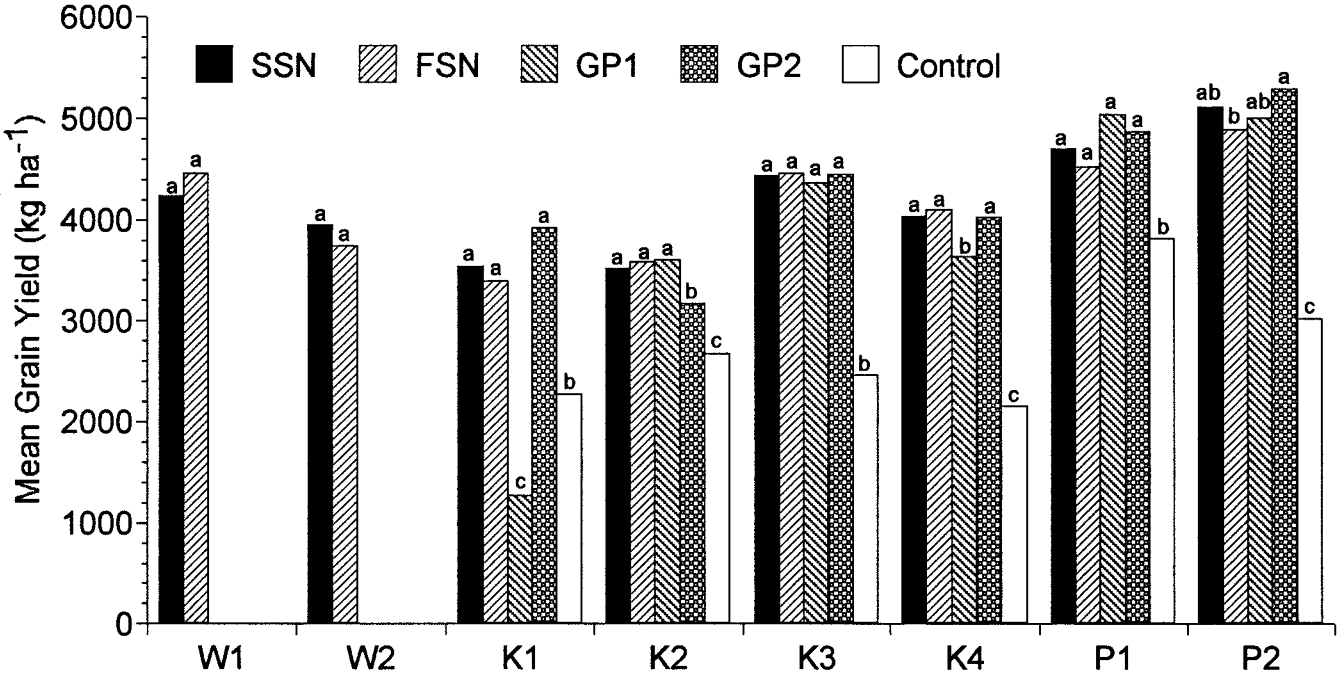

Fig. 3. Mean grain yield by N management system at each of the eight sites.

N rate of 134.7 kg N ha^{-1}, FSN and SSN reduced N applied by 15.0 and 7.9%, respectively (Table 2).

Grain yields for SSN, FSN, and GP2 (3531, 3385, and 3912 kg ha^{-1} respectively) were not significantly different (Fig. 3). Interestingly, GP1 had a significantly lower yield (1264 kg ha^{-1}) that was even below that of the control (2271 kg ha^{-1}). At this site, a late-spring freeze occurred on 16 Apr. 2001. The GP1 system applied 134.7 kg N ha^{-1} about two months earlier at GS 25. This N application accelerated crop growth and development, and therefore, wheat in this system was at anthesis when the freeze occurred, resulting in anther damage and pollen sterility. The FSN and GP2 systems delayed N application until GS 30 and subsequently delayed anthesis enough to miss the freeze. In SSN, 28% of the management units had GS-25 tiller densities below the critical threshold, and a low rate of 67 kg N ha^{-1} was applied only to these areas (Table 2). Apparently, the reduced GS-25 N rate and/or the limited spatial coverage used in SSN compared with GP1 prevented freeze damage and preserved the crop's yield potential.

Spring N use efficiency was not significantly different among SSN, GP1, and GP2 (47.4, 42.6, and 37.4%, respectively, Fig. 4). However, when the late-spring freeze caused pollen sterility and low grain yield in GP1, the crop remained in a vegetative state, resulting in increased straw yield and straw N concentration compared with the other systems (data not shown). This resulted in a high GP1 SNUE (42.6%) that was not correlated with high grain yield. Interestingly, SSN SNUE (47.4%) was significantly higher than FSN SNUE (29.1%) even though grain yields were similar and SSN applied slightly higher N rates (Fig. 3 and Table 2). The SSN management system had significantly higher straw and grain N concentrations that may have resulted from the early (GS 25) N application in 28% of the SSN management units.

Within-field grain yield variance was lowest in GP1 and the control (Table 3). This is consistent with yield in these systems being limited by either freeze damage (GP1) or severe N deficiency (control). Among the other systems, SSN had the lowest within-field variance (1 936 594 kg^2 ha^{-2}) compared with FSN (3 544 998 kg^2 ha^{-2}) or GP2 (3 170 156 kg^2 ha^{-2}). This supports the contention that SSN successfully identified and corrected areas of low tiller density and whole-plant N concentration, resulting in more spatially uniform grain yield.

K2

The mean FSN and all SSN management units had GS-25 tiller densities below threshold (Table 2), and both systems received a GS-25 N application of 67 kg ha^{-1}. The GP1 system received 134.7 kg N ha^{-1} at GS 25 as defined.

Until GS 30, both SSN and FSN were managed identically, and there was not a significant difference in mean whole-plant N concentration at GS 30 (Table 2). The SSN histogram (Fig. 2) indicates that whole-plant N concentration at GS 30 ranged from 32.9 to 51.8 g kg^{-1}, corresponding to a range in GS-30 N rates of 0.0 to 77.1 kg N ha^{-1}. The histogram also indicates that a uniform N application based on the FSN mean overapplied N to 91.4% of the field. Similar to W1 and W2, the histogram for K2 (Fig. 2) is based on too small a sample size for statistics of skewness to be reliable, but it does appear to be skewed to the left, which may explain why SSN resulted in reduced N rates compared with FSN (86.7 and 99.9 kg N ha^{-1}, respectively).

At K2, there was not a significant difference in grain yield among SSN, FSN, and GP1 (3507, 3574, and 3602 kg ha^{-1}, respectively; Fig. 3), which all had higher grain yields than GP2 (3161 kg ha^{-1}) and the control (2667

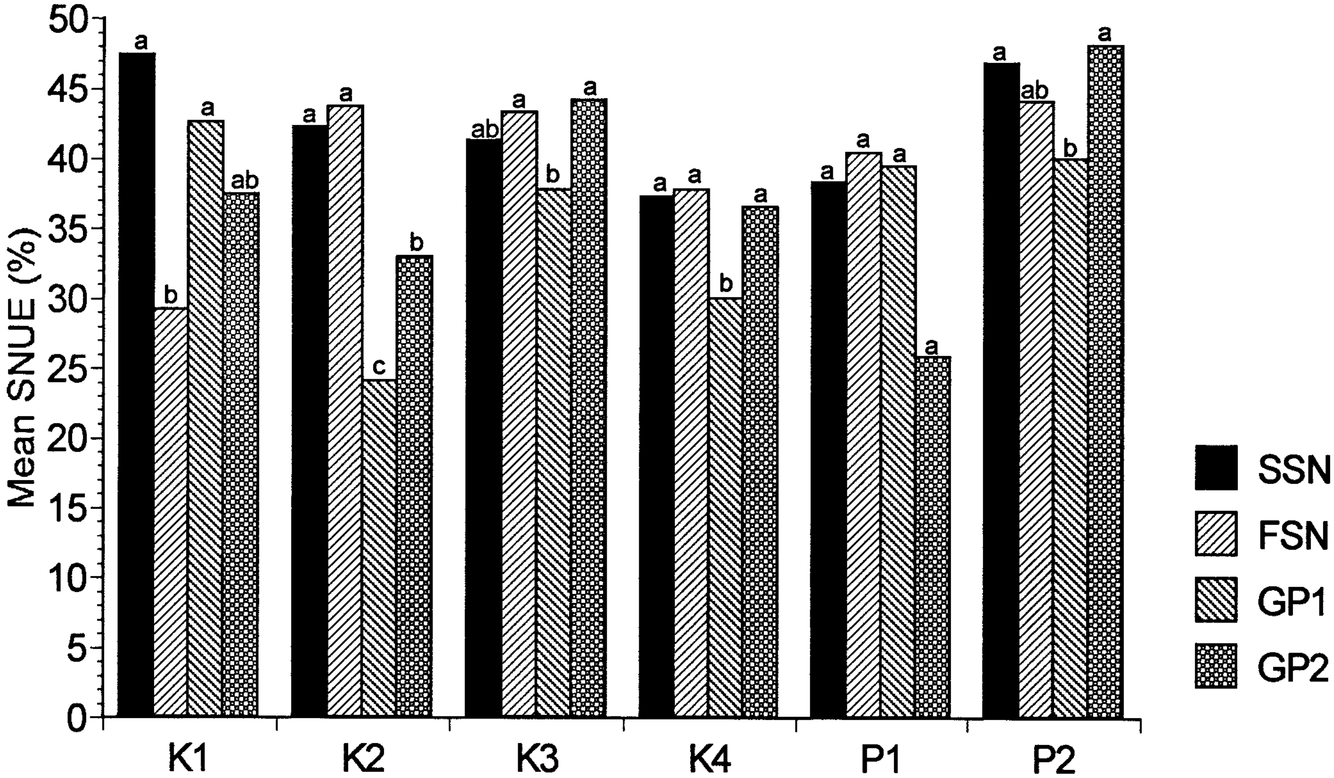

Fig. 4. Mean spring N use efficiency (SNUE) by N management system at six sites.

kg ha^{-1}). There were low GS-25 tiller densities at the site, and SSN, FSN, and GP1 all applied GS-25 N, which may have stimulated tiller development and increased grain yield. The SSN and FSN systems also reduced total spring N applied by 35.6 and 25.8%, respectively, compared with GP1 and GP2 (Table 2).

Both SSN and FSN had significantly higher SNUE (42.2 and 43.7%, respectively) compared with GP1 and GP2 (24.1 and 33.0%, respectively) (Fig. 4). This is likely due to the reduction in spring N applied by SSN and FSN. However, there was not a difference in SNUE between SSN and FSN (Fig. 4). Table 3 shows that within-field variability in grain yield was minimized by SSN (137 257 kg^2 ha^{-2}) compared with FSN (159 601 kg^2 ha^{-2}), GP1 (201 171 kg^2 ha^{-2}), GP2 (405 519 kg^2 ha^{-2}), and the control (667 122 kg^2 ha^{-2}) systems. These results support the contention that SSN successfully identified and corrected areas of low tiller density and whole-plant N concentration, resulting in maximized SNUE and a more spatially uniform grain yield.

K3

Mean FSN and all SSN management units had GS-25 tiller densities above the threshold (Table 2), and therefore, a GS-25 N application was not applied to either system. A total of 134.7 kg N ha^{-1} was applied to GP1 at GS 25 as defined.

Until GS 30, both SSN and FSN were managed identically, and there was not a significant difference in mean whole-plant N concentration at GS 30 (Table 2). The SSN histogram (Fig. 2) indicates that whole-plant N concentration at GS 30 ranged from 17.9 to 22.5 g kg^{-1}, corresponding to GS-30 N rates of 127.0 to 134.7 kg N ha^{-1}. The histogram also indicates that the mean FSN whole-plant N concentration at GS 30 is greater than 53.3% of the SSN management unit whole-plant N concentrations at GS 30. However, 39% of the these SSN management units had GS-30 whole-plant N concentrations below 20.9 g kg^{-1}, which corresponds to the maximum recommended GS-30 N rate (134 kg ha^{-1}; Fig. 1).

Table 3. Within-field grain yield variance (mean squares) by N management system [SSN: site-specific N management; FSN: field-specific N management; GP1: a typical grower's practice applied at growth stage (GS) 25; GP2: a typical grower's practice applied at GS 30; Control: did not receive any spring N] determined using general linear models for six sites.

	Within-field grain yield variance (kg^2 ha^{-2})					
N management system	K1	K2	K3	K4	P1	P2
SSN	1 936 594	137 257	206 495	283 420	731 833	1 001 987
FSN	3 544 998	159 601	80 658	471 555	951 713	344 973
GP1	1 328 441	201 171	104 336	274 714	186 568	365 676
GP2	3 710 156	405 519	216 668	388 772	164 566	582 613
Control	735 974	667 122	205 776	192 283	3 571 310	1 632 695

Consequently, FSN overapplied N to only 13.3% of the field.

The SSN, FSN, GP1, and GP2 systems all had similar grain yields (4431, 4458, 4357, and 4446 kg ha^{-1}, respectively) that were significantly higher than the control (2451 kg ha^{-1}; Fig. 3). At this site, early-season growing conditions were ideal, resulting in above-threshold tiller densities at GS 25 and low whole-plant N concentrations at GS 30, indicating a high yield potential that required a high GS-30 N rate. Therefore, there was little or no difference among the SSN, FSN, GP1, and GP2 systems in total N applied (Table 2).

While there was little difference in total N applied among management systems, there was a difference in N timing. By waiting until GS 30 to apply N, SNUE was significantly higher in SSN, FSN, and GP2 (41.3, 43.3, and 44.2%, respectively) compared with GP1 (37.8%; Fig. 4). This increased SNUE was due to increased grain and straw N concentrations (data not shown) for SSN, FSN, and GP2 compared with GP1. Interestingly, FSN reduced within-field grain yield variance (80 658 kg^2 ha^{-2}) compared with SSN (206 495 kg^2 ha^{-2}), GP1 (104 336 kg^2 ha^{-2}), GP2 (216 668 kg^2 ha^{-2}), and the control (205 776 kg^2 ha^{-2}; Table 3). Therefore, FSN reduced within-field grain yield variance compared with all other systems at this site.

K4

The mean FSN GS-25 tiller density was above threshold (Table 2) and therefore did not receive a GS-25 N application. A small portion (3%) of the SSN management units had GS-25 tiller densities below threshold (Table 2) and received 67 kg N ha^{-1} at GS 25. As defined, GP1 received 134.7 kg ha^{-1} at GS 25.

Until GS 30, both the SSN and FSN were managed similarly, with only 3% of the SSN management units receiving a GS-25 N application. Therefore, there was not a significant difference in mean whole-plant N concentration at GS 30 between SSN (17.9 g kg^{-1}) and FSN (17.5 g kg^{-1}; Table 2). The GP1 system applied GS-25 N and had a significantly higher mean whole-plant N concentration at GS 30 (33.0 g kg^{-1}) compared with all other systems. The SSN histogram for K4 (Fig. 2) indicates that whole-plant N concentration at GS 30 ranged from 15.9 to 26.0 g kg^{-1}, corresponding to GS-30 N rates of 110.2 to 134.7 kg N ha^{-1}. Because 3% of the SSN management units received GS-25 N, this histogram could not be used to estimate the frequency distribution of FSN whole-plant N concentration at GS 30 or the fraction of the field to which FSN may have over- or underapplied N (i.e., the distribution of SSN whole-plant N concentration at GS 30 was not the same as that of FSN whole-plant N concentration at GS 30). However, similar to K3, the early-season growing conditions were ideal at this site and resulted in the maximum allowed GS-30 N rate of 134.7 kg ha^{-1} for both the SSN and FSN systems (Table 2).

Grain yields were similar for SSN, FSN, and GP2 (4031, 4089, and 4017 kg ha^{-1}, respectively; Fig. 3) due to the identical N application rate and similar timing for all three systems. The GP1 and control systems had significantly lower grain yields (3628 and 2150 kg ha^{-1}, respectively) compared with SSN, FSN, and GP2. Similar to grain yield, SNUE was significantly higher for SSN, FSN, and GP2 (37.3, 37.7, and 36.5%, respectively) compared with GP1 (30.0%; Fig. 4). The lower SNUE for GP1 was due to decreased grain yield (Fig. 3) and grain N concentration (data not shown) compared with SSN, FSN, and GP2. These results show that by properly timing N applications and optimizing N rates, SSN maximizes both grain yield and SNUE.

The control (192 283 kg^2 ha^{-2}) minimized within-field variance in grain yield compared with SSN (283 420 kg^2 ha^{-2}), FSN (471 555 kg^2 ha^{-2}), GP1 (274 714 kg^2 ha^{-2}), and GP2 (388 772 kg^2 ha^{-2}). This is consistent with grain yield in the control being uniformly limited by N deficiency. Among systems that had high grain yield, SSN minimized within-field variance compared with FSN and GP2. These results support the contention that under high-yielding conditions, SSN results in a more spatially uniform grain yield.

P1

The mean FSN and all SSN management units had GS-25 tiller densities below the threshold (Table 2), and 67 kg N ha^{-1} was applied. A total of 134.7 kg N ha^{-1} was applied to GP1 at GS 25. At GS 30, mean whole-plant N concentration was consistent with N rates applied to each system at GS 25. The GP1 system received the highest GS-25 N rate and had the highest mean whole-plant N concentration at GS 30 (60.0 g kg^{-1}). The FSN and SSN systems, which had lower N rates applied, had intermediate whole-plant N concentrations (51.5 and 52.2 g kg^{-1}, respectively). The GP2 and control systems, which did not receive any GS-25 N, had the lowest mean whole-plant N concentrations (38.6 and 39.6 g kg^{-1}, respectively).

The GP2 and control whole-plant N concentrations approximated the reported GS-30 N sufficiency levels of 35.0 g kg^{-1} (Roth et al., 1989), 40.0 to 50.0 g kg^{-1} (Donohue and Brann, 1984), and 39.5 g kg^{-1} (Baethgen and Alley, 1989a, 1989b) for soft red winter wheat. This indicated that P1 had a large N carryover from the previous corn crop. The SSN histogram (Fig. 2) shows that whole-plant N concentration at GS 30 ranged from 37.7 to 59.2 g kg^{-1}, corresponding to recommended N rates from 0.0 to 54 kg N ha^{-1}. However, most of the SSN management units (and the mean FSN value) had whole-plant N concentrations above 48.9 g kg^{-1} (Fig. 2), which corresponded to a recommended N rate of 0.0 kg N ha^{-1}. Consequently, FSN did not apply any GS-30 N even though 29.2% of the land area would be expected to respond to a N application (Fig. 2).

The SSN, FSN, GP1, and GP2 systems all had similar grain yields (4695, 4520, 5033, and 4863 kg ha^{-1}, respectively), which were significantly higher than the control (3808 kg ha^{-1}; Fig. 3). Consistent with basing N rates on in-season evaluation of crop N status under conditions of high N carryover, both FSN and SSN reduced spring N applications by 48.6 and 45.7%, respectively, compared with either GP1 or GP2 (Table 2).

There was not a statistical difference in SNUE among

SSN, FSN, GP1, and GP2 (38.3, 40.4, 39.4, and 25.8%, respectively; Fig. 4). This is surprising given the large reduction in spring N applied without a significant reduction in grain yield for SSN and FSN. The lack of statistical separation of means may have been caused by a high degree of variability in SNUE at this site. The coefficient of variation for SNUE at P1 was 53.2% compared with 18.4% at K1, 18.0% at K2, at 10.4% K3, 6.4% at K4, and 11.6% P2. This large coefficient of variation may have been due to the large within-field grain yield variability in the control (3 571 310 $kg^2\ ha^{-2}$; Table 3) compared with the other systems (731 833, 951 713, 186 568, and 164 566 $kg^2\ ha^{-2}$ for SSN, FSN, GP1, and GP2, respectively). The control plots would have such an impact on SNUE because their values are used to calculate SNUE (Eq. [1]).

Table 3 shows that GP1 and GP2 minimized within-field variance (186 568 and 164 566 $kg^2\ ha^{-2}$, respectively) of grain yield compared with SSN, FSN, and the control (731 833, 951 713, and 3 571 310 $kg^2\ ha^{-2}$). This may indicate that the high N application rates applied in the GP1 and GP2 systems combined with the N carryover maximized grain yield across the site, resulting in small within-field variance. This may have masked any benefit of using a SSN or FSN system but would also indicate that the SSN and FSN systems did not fully optimize N rates throughout the field. However, SSN did reduce within-field variability compared with FSN and the control, indicating that SSN improved the optimization of N rates compared with FSN.

P2

Mean FSN and all SSN management units had GS-25 tiller densities above threshold (Table 2) and did not receive a N application at GS 25. The GP1 system received 134.7 kg N ha^{-1} at GS 25 as defined.

Until GS 30, both the SSN and FSN systems were managed identically, and therefore, there was no significant difference in mean whole-plant N concentration at GS 30 between these systems (Table 2). The GP1 system applied GS-25 N and had a significantly higher mean whole-plant N concentration at GS 30 (33.4 g kg^{-1}) than all other systems. The SSN histogram (Fig. 2) shows that whole-plant N concentration at GS 30 ranged from 17.1 to 29.2 g kg^{-1}, corresponding to recommended GS-30 N rates of 94.8 to 134.7 kg N ha^{-1}. The histogram also indicates that a uniform N application based on the mean FSN whole-plant N concentration at GS 30 would overapply N to 48.0% of the field.

Grain yields were similar for SSN, GP1, and GP2 (5104, 4999, and 5290 kg ha^{-1}, respectively) and were significantly higher than the control (3018 kg ha^{-1}; Fig. 3). Surprisingly, a reduction in grain yield was found in FSN (4884 kg ha^{-1}) compared with GP2, despite similar timings and rates of N application. The SSN system reduced total N applied by 5.3% compared with either GP1 or GP2 (Table 2) without a significant reduction in grain yield. The SSN, FSN, and GP2 systems all had similar SNUE (46.8, 44.1, and 48.1%, respectively) that were significantly greater than GP1 (40.0%; Fig. 4). By delaying N application until GS 30, the SSN, FSN, and GP2 systems were able to significantly increase grain N concentration (data not shown) compared with GP1. This increase in grain N concentration accounted for the increase in SNUE seen in SSN, FSN, and GP2. Interestingly, FSN minimized within-field variance in grain yield (344 973 $kg^2\ ha^{-2}$) compared with SSN (1 001 987 $kg^2\ ha^{-2}$), GP1 (365 676 $kg^2\ ha^{-2}$), GP2 (582 613 $kg^2\ ha^{-2}$), and the control (1 632 695 $kg^2\ ha^{-2}$; Table 3). Therefore, while there was little difference between the timing and rate of N application between systems (Table 2), FSN was found to maximize SNUE and reduce within-field grain yield variance compared with all other systems.

CONCLUSION

If site-specific management is to improve production over traditional field-wide systems, it is essential to have within-field variability in the factors being studied. At six of the eight sites, FSN and SSN GS-25 recommendations based on tiller density were identical, indicating that in many circumstances, within-field variability in this parameter may not be of great agronomic significance. This is likely due to making N application decisions based on simple above- or below-threshold criteria. This was not the case at GS 30. Within-field whole-plant N concentration at GS 30 was highly variable at all sites (Fig. 2), and whole-field N management (FSN) overapplied N to 75.0, 82.6, 91.4, 13.3, and 48% of the land area at W1, W2, K2, K3, and P2, respectively. Sufficient variability was present in these fields to test the effectiveness of SSN.

Our first objective was to determine if a site-specific N application based on the Weisz and Heiniger (2000) in-season management system (Fig. 1) would increase grain yield compared with either a field-specific application based on the same logic or typical growers' practices. At all sites, SSN and FSN grain yields were not significantly different. The SSN system did not improve grain yields compared with field-wide management based on the same in-season estimation of optimum N rates.

At sites where SSN and FSN were compared with typical growers' practices, grain yield benefits of in-season N optimization were apparent (Fig. 3). At K1, where spring-freeze damage severely reduced grain yield in GP1, both FSN and SSN systems correctly timed and/or spatially located N applications and rates to avoid the freeze damage. At K2, where GS-25 tiller density was below threshold, both FSN and SSN systems correctly timed GS-25 N applications and resulted in higher grain yield compared with GP2. At K4, where GS-25 tiller density was above threshold, both SSN and FSN systems correctly delayed application of N until GS 30 and resulted in increased grain yield compared with GP1. In terms of grain yield, these results indicate that the use of in-season optimization of N rates is more important than site-specific N management.

Our second objective was to determine if site-specific N management reduced N input compared with either a field-specific application based on the same logic or typical growers' practices. At sites where typical growers' practices were included, SSN and FSN both reduced total spring N rates compared with both growers' practices (GP1 and GP2) at four of the six sites (Table 2). The reduction in total spring N ranged from 2.2% to 48.6%. Consequently, a large decrease in N rate appeared to result from using an in-season system to evaluate the crop and optimize N rates compared with typical growers' practices.

While SSN consistently reduced N inputs compared with typical growers' practices, its performance was more complex when compared with FSN. At five sites, SSN reduced N inputs compared with FSN by 19.6, 16.5, 13.2, 0.3, and 3.2% (Table 2). At two sites (K1 and P1), SSN resulted in a slight increase in total spring N applied compared with FSN (8.2 and 5.6%, respectively). The increase in N input at K1 resulted from 28% of the SSN management units having below-threshold values of GS-25 tiller density and receiving a GS-25 N application of 67 kg N ha^{-1} compared with FSN, which did not receive any GS-25 N. At P1, 29.2% of the SSN management units had GS-30 whole-plant N concentrations below 48.9 g kg^{-1} and received a GS-30 N application compared with FSN that did not receive any GS-30 N. These increases in N input at K1 and P1 did not result in increased grain yield (Fig. 3) compared with FSN; however, they did result in a more spatially uniform grain yield (Table 3) compared with FSN.

Our third objective was to determine if site-specific N applications increased SNUE compared with either a field-specific N application based on the same logic or typical growers' practices. At all sites where SNUE was determined, SSN maximized SNUE (Fig. 4).

Our final objective was to determine if site-specific N application reduced within-field grain yield variability. At four sites, SSN reduced within-field grain yield variability compared with FSN (Table 3). However, at the other two sites, FSN or typical growers' practices minimized within-field grain yield variability.

In conclusion, our results indicate that when N management decisions are based on in-season systems that optimize N rates, they have the potential to greatly reduce N inputs (up to 48.6%) compared with typical growers' practices. These results may also explain the studies of Mulla et al. (1992), Bhatti et al. (1998), Stone et al. (1996), and Raun et al. (2002), which found reduced N inputs compared with typical growers' practices but confounded site-specific N management and pre- or in-season estimates of crop N status. By separating these confounded effects, our data indicate that under many circumstances, site-specific N management may further reduce N inputs (up to 19.6%) compared with field-specific management.

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